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INTERNATIONAL ENERGY AGENCY
HYDROGEN IMPLEMENTING AGREEMENT
TASK 11: INTEGRATED SYSTEMS

Final report of Subtask A:
Case Studies of
Integrated Hydrogen Energy Systems

Chapter 10 of 11

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Chapter 10
PALM DESERT RENEWABLE HYDROGEN TRANSPORTATION PROJECT

1. PROJECT GOALS

The Palm Desert Renewable Hydrogen Transportation Project encompasses the entire energy cycle, from production to end-use. At the proposed solar hydrogen generation facility, a solar array will generate electricity to run an electrolyzer, which will produce hydrogen from water. The hydrogen will be compressed and stored. The stored hydrogen will then be delivered to the dispensing station where it is used to fuel a fleet of fuel cell vehicles. A pictorial representation of the system is shown in Figure 10.1. This transportation system allows the city to use the energy from the sun to power vehicles whose only exhaust is pure water. This demonstration is the first of its type in the United States.

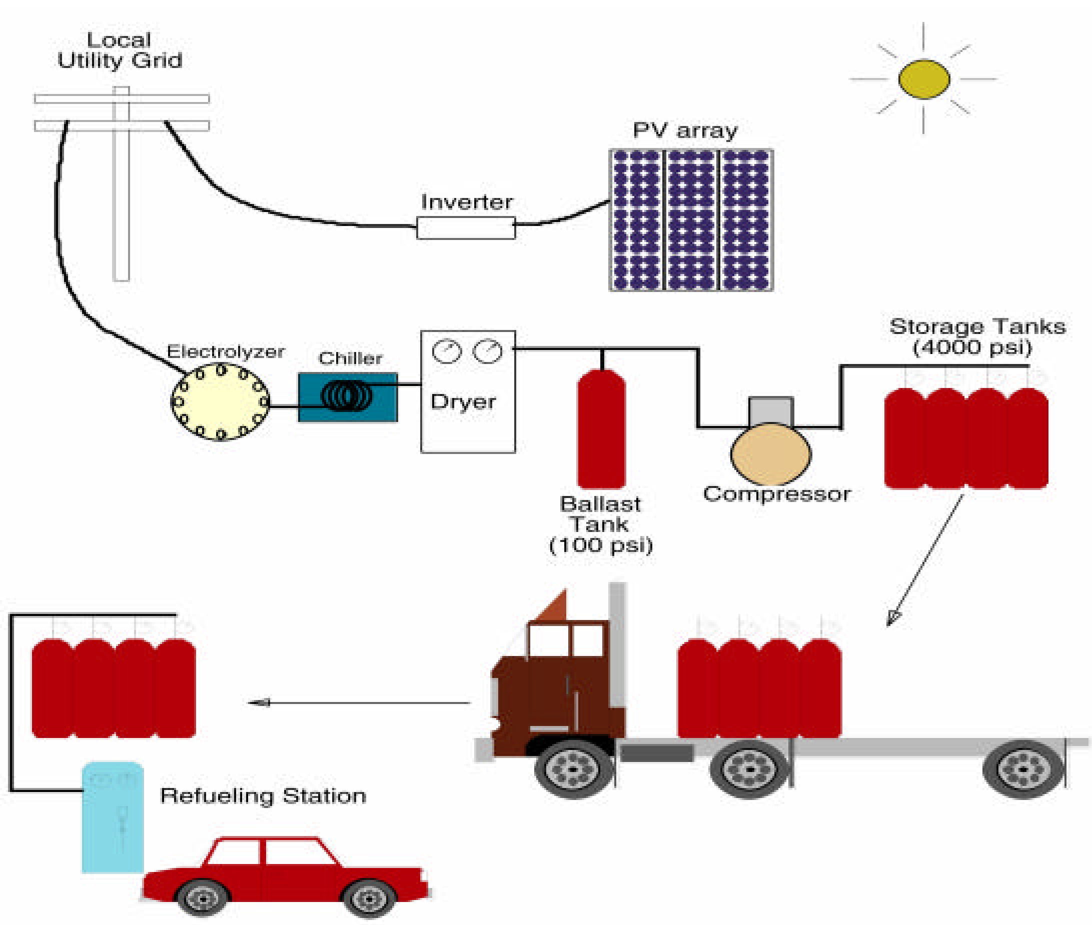

Figure 10.1: Block diagram of proposed hydrogen generation and refueling facilities

The streets of Palm Desert are the test site for the project's mini-fleet of fuel cell-powered, zero emission vehicles. This fleet was complete as of April 24, 1998 and consists of 3 golf-cart-sized personal utility vehicles (PUVs) and 1 neighborhood electric vehicle (NEV). The city is a natural venue for the project because of its good solar insolation, its location in the South Coast Air Basin where air quality is an important issue, and its commitment to environmental technology.

The solar hydrogen generation facility will be sited at SunLine Transit Agency in Thousand Palms, immediately adjacent to Palm Desert. SunLine is the home of a fleet of forty compressed natural gas (CNG) transit buses, the nation's first fleet to convert entirely to CNG. The site currently contains the refueling infrastructure for the buses, so the addition of a solar hydrogen generation facility is a natural step in the company's progression toward alternative fuel transportation systems.

The hydrogen dispensing station will be located at the Palm Desert Civic Center electric vehicle recharging station near City Hall. This site is adjacent to the city park where the PUVs are used and is near the storage area for the PUVs and the NEV. This site was chosen partly for its convenient access and partly as a result of negotiations between Schatz Energy Research Center (SERC) and the City of Palm Desert. This location is a central one that facilitates demonstration and public viewing of the dispensing station.

The objectives of the Palm Desert Renewable Hydrogen Transportation Project are:

- the development and demonstration of fuel cell powered vehicles
- the renewable generation of hydrogen
- the nurturing of new high-tech activities that benefit the environment

2. GENERAL DESCRIPTION OF PROJECT

This project was begun in January 1996 and is scheduled for completion in March 1999. Participants in the project include the U.S. Department of Energy (DOE), the Schatz Energy Research Center (SERC), the South Coast Air Quality Management District (SCAQMD), the City of Palm Desert, SunLine Transit Agency, W.L. Gore & Associates, ASE Americas, DuPont, and Teledyne Brown Engineering.

The first phase of this project entailed the design and construction of the three PUVs. Each PUV consists of a standard E-Z-Go electric golf cart that was converted from pure battery operation to operation with a proton exchange membrane (PEM) fuel cell with a very small battery to supply peak loads. This vehicle has a top speed of 13 mph and a range of 15 miles.

The second phase involved the design and construction of an NEV. This vehicle consists of a Kewet (Danish) electric vehicle that was converted in a manner similar to the PUVs. It has a top speed of 35 mph and a range of 30 miles.

All four of these vehicles are currently seeing daily use in Palm Desert.

The final phase of the project consists of the design and construction of a solar hydrogen generation station and a hydrogen refueling station. The design portion of this phase is complete while the actual construction awaits final funding from the DOE.

In conjunction with the delivery of the first vehicle, it was necessary to construct a temporary refueling station so that they could be readily refueled prior to the construction of the solar hydrogen generation station and refueling station. This was done by designing a multi-tank cascade system that utilizes commercially available hydrogen cylinders. This system allows the vehicles to be refueled to approximately 2,000 psig in a matter of minutes. The permanent refueling station will enable us to fill the NEV tanks to 3,000 psig, its design pressure, while the PUVs will continue to be filled to 2,000 psig.

3. DESCRIPTION OF COMPONENTS

3.1 Vehicles

3.1.1 Personal Utility Vehicles

As the first step in the design and construction of the SERC prototype fuel cell PUV, we selected the E-Z-GO golf cart to serve as the platform because it was already established and accepted in the Palm Desert community and used an efficient motor and motor controller. We have added all features necessary to make the cart street-legal in the City of Palm Desert, such as headlights and turn signals, a rear view mirror, seat belts, and brake lights. We then instrumented and tested an original battery-powered E-Z-Go Golf Cart. This provided information on the performance and power demands that the PUV fuel cell power plant would have to satisfy and allowed preliminary system design and sizing of the proton exchange membrane (PEM) fuel cell stack required for the prototype.

Based on these tests, we developed a parallel hybrid design for the system that incorporates three small lead acid batteries to provide power for acceleration and hill climbing. In this role, the batteries provide a small buffer for short-term power demands and are recharged during normal cruising and idling conditions (Picture 10.1).

Picture 10.1: Personal Utility Vehicle with City of Palm Desert Economic Development Director Paul Shillcock commuting to work.

Control of the system was assigned to an on-board computer that permits the PUV operator to start and drive the cart in a straightforward manner. The control computer also provides a laptop computer with real-time information on the status of all PUV systems. The laptop both displays and stores the data for further analysis. The design of the PUV systems and the control software have been reviewed and revised to protect the operator and the PUV by the use of inherently safe hardware design and numerous software safety interlocks.

The PEM stacks developed for powering the PUVs have been designed by SERC to be simple and to have high net efficiency. Consequently, they are designed to run efficiently on air at very low pressure. Although this entails some sacrifice in stack performance relative to high pressure fuel cells, a simple, low power blower (instead of a compressor) can be used to provide the air supply. The small power demand of the blower results in high net efficiency.

The fuel cell stack developed for and used in the prototype was designed:

- to operate throughout the entire range of driving conditions at a voltage compatible with the E-Z-GO motor controller
- to provide sufficient power to cruise at constant speed up a mild incline and still charge the batteries
- to require low parasitic loads for auxiliary systems such as air supply, water circulation, control computer, solenoids, sensors, etc.
- to operate efficiently

To meet these demands, the resulting fuel cell stack contains 64 cells with 300 cm^2 active area. Each cell consists of a membrane and electrode assembly (MEA) that is composed of a DuPont Nafion™ 115 membrane and E-TEK ELAT gas diffusion media. We have altered the platinum catalyst loading on these ELAT's over time. Our initial, or prototype stack, had loadings of 2 mg/cm^2 on the hydrogen side, and 5 mg/cm^2 on the oxygen side. This stack had a peak of output of 4.80 kW_p. We began reducing these loadings with the stack for PUV 1 that had 2 mg/cm^2 platinum loading on both sides of the MEA. This stack produced 5.67 kW_p. Following this success, we further reduced the loadings for PUV's 2 and 3 to 1mg/cm^2 platinum on each side. These stacks also produced 5.67 kW_p.

A typical interaction of the battery and fuel cell during a normal standing start of the PUV is shown in Figure 10.2. The power supplied by the fuel cell is in green, that supplied by the battery is in red. The traction bus power, which is the total power being supplied to the vehicle, is in black. As can be seen from this graph, prior to the beginning of acceleration, the fuel cell is producing approximately 0.75 kW, which is being used to top off the battery and to power parasitic loads such as the blower, solenoids, etc.

The highest power demand occurs during the first second of acceleration. During this initial surge, the battery supplies 5 kW of power to the traction bus, while the fuel cell supplies only about 1 kW. However, after only three seconds, the power demand has dropped considerably, while the fuel cell has ramped up its output to just over 2 kW. This demonstrates the dynamic interplay between the batteries, which are able to provide large amounts of instantaneous power, and the fuel cell which is comparatively slow to respond, but which can provide long term continuous power. After only 10 seconds, the vehicle has reached cruising speed, the traction bus power demand has dropped to 1.6 kW and the fuel cell is not only providing the sole source of power to the vehicle, but is now recharging the battery.

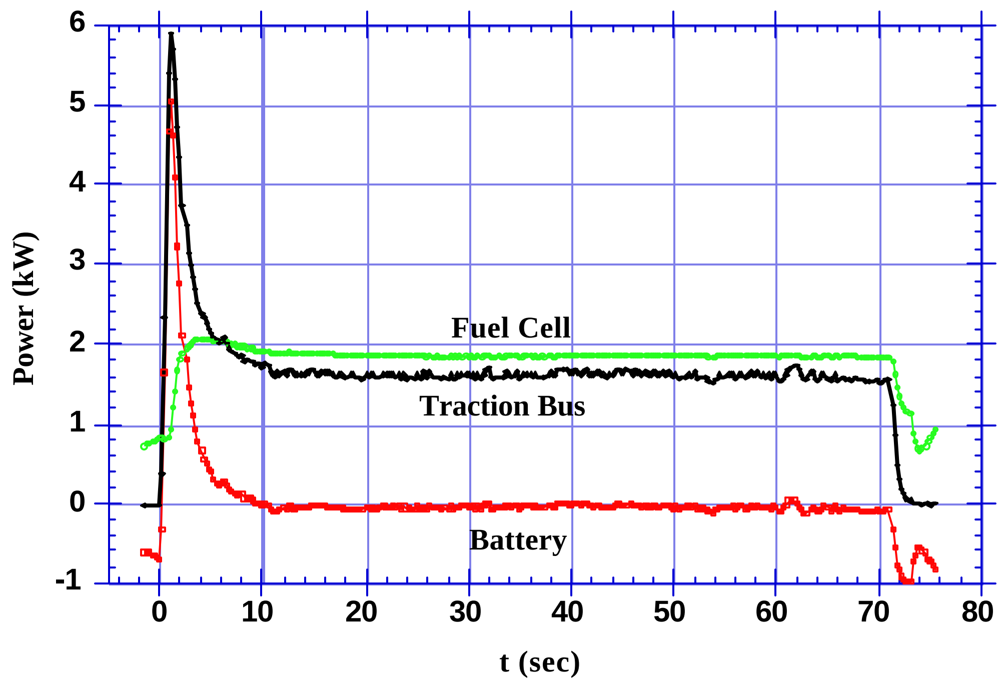

Figure 10.2: Fuel Cell Response during Acceleration

3.1.2 Neighborhood Electric Vehicle

As with the PUVs, the first step involved selecting a base vehicle. We chose the Danish made Kewet because it was a readily available, relatively inexpensive, mass-produced vehicle already being used in Europe exactly as we intended to use it in Palm Desert. Further, and perhaps most importantly, the United States Department of Transportation has certified it as a street legal vehicle in this country.

This vehicle is fully enclosed, unlike the PUVs that do not have doors. It also comes with seat belts and turn signals already installed (Picture 10.2).

As with the PUVs, the vehicle was first instrumented and tested to determine its power requirements and a fuel cell was then built to accommodate them. The main differences between the NEV stack and those in the PUVs are number of cells and membrane material. All of the PUV stacks were made with DuPont Nafion™ 115 while this one uses Gore PRIMEA™ membrane and electrode assemblies. This material provides a higher power density which means that the stack runs more efficiently (uses less hydrogen per mile) and is able to charge the batteries more often.

Specifications for the PUVs and the NEV are given in Table 10.1.

All of the vehicles have been in service for some time now in Palm Desert. PUV1 is used as a daily commute vehicle while PUV's 2 & 3 are used by city personnel for park maintenance. The NEV is used by city officials for routine errands. We have collected a substantial amount of data in this time, which is summarized in Table 10.2. Note that these are real world data, collected while the vehicles were being used by ordinary, non-technical city employees.

Picture 10.2: Neighborhood Electric Vehicle

Table 10.1: Specifications for PUVs and NEV

	PUVs	NEV
Membrane Material	DuPont Nafion™ 115	Gore PRIMEA™
Number of Cells	64	96
Fuel Cell Power @ 600 mV/cell	4.0 kW	9.0 kW
Active Area	300 cm^2	300 cm^2
Fuel Cell Operating Temperature	50 - 60°C (120 – 140 F)	50 - 65°C (120 - 150 F)
Body and Chassis	E-Z-Go Golf Cart	Kewet El-Jet 3
Traction Bus Voltage (nominal)	36 V	48 V
Electric Motor Size	1.5 kW (2.0 hp)	7.5 kW (10 hp)
Top Speed	13 mph (21 km/h)	35 mph (56 km/h)
Range	15 mi (24 km)	30 mi (48 km)
Hydrogen Tank Volume	14 liters	31.1 liters
Gas Storage Pressure	2,000 psig (138 bar)	3,000 psig (207 bar)

Table 10.2:Summary of PUV and NEV Performance in Palm Desert

Vehicle	Delivery Date	Months of Operation	Total Miles (Aug. '98)		Maximum speed		Mileage (mpg equivalent)			
							City		Highway	
			mi	km	mph	km/h	mpg	km/l	mpg	km/l
PUV1	Sept.1996	25	450	724	13	21	65	28	110	47
PUV 2	May 1997	17	450	724	15	24	95	40	120	51
PUV 3	May 1997	17	510	821	15	24	90	38	120	51
NEV	April 1998	6	160	257	35	56	50	21	70	30

3.2 Hydrogen Generation Station

The generation facility consists of a gas generation building, a photovoltaic (PV) array, and the gas processing and storage area. The generation building will house the electrolyzer and related control and monitoring systems. The gas processing and storage area will contain a hydrogen gas compressor and a gas storage unit comprised of four high-pressure storage cylinders. A dispensing unit will be used to refuel the vehicles at a site near City Hall in Palm Desert.

The 430 square foot gas generation building will consist of three rooms: an office/control room, a restroom, and a gas generation room. The office/control room will house a control computer, electrical control and alarm panels, and general office equipment. The gas generation room will contain an electrolytic hydrogen generator and a hydrogen dryer system, both manufactured by Teledyne Brown Engineering. The electrolyzer will produce hydrogen gas at a rate of 20 standard liters per minute (slm) and a pressure of 100 psig. Initially, only sufficient hydrogen to refuel the vehicles will be produced. Eventually, the electrolyzer may run up to 24 hours per day to produce enough gas for SunLine Transit's needs. The electrolyzer and the dryer both have their own programmable logic controllers (PLCs) which will control their operation and will be interfaced with the facility control computer. A one-hour fire wall will separate the gas generation room from the control room and restroom.

The gas generation building will also contain the facility monitoring and data collection systems. These will measure and record various pressures, temperatures, gas flow rates, and power to and from certain components. In addition to providing important input to the safety system, the data will make possible such calculations as net system and component efficiencies.

3.2.1 PV Array

The photovoltaic array will consist of three flat-plate, fixed position, sub-arrays, each of which contains 13 ASE-300 DG/50 modules in parallel. These modules are manufactured by ASE Americas and operate at a nominal 48 V_{DC} and have a peak power rating of 300 W. Each subarray will have a peak power capability of 3.9 kW at 48 V, for a total system output of 11.7 kW.

ASE Americas employs environmentally benign procedures to produce their PV wafers, so there is no hazardous waste stream and the final product contains no hazardous materials. These are state-of-the-art, high efficiency modules designed for utility applications. ASE Americas has agreed to share the cost of these modules and has been an industrial partner since this project began.

3.2.2 Inverters

Each subarray will be connected to a Trace SW5548UPV 4kW peak-power tracking sine wave inverter. These inverters are designed and approved for utility grid intertie. They will receive the nominal 48 V output from the sub-arrays and in turn produce 240 V_{AC} power, which will be connected to Sunline's grid for on-site consumption.

3.2.3 Electrolyzer

In the past, SERC has worked closely with Teledyne Brown Engineering on the solar hydrogen project at the Humboldt State University Telonicher Marine Laboratory. The project uses a solar hydrogen/fuel cell system to run the air compressor that aerates the fish tanks.

One of the main components of the system is Teledyne's Altus 20 electrolyzer. Nearly eight years of experience operating, monitoring, and modeling the system indicates that the unit works well in automatic and independent operation with a PV array. This electrolyzer is a medium pressure, bipolar, alkaline unit. It consists of a 12-cell electrolysis module designed to deliver 20 slm of H_2 gas at a current of 240 A at 24 V_{DC}. Hydrogen is produced by the module at 100 psig. The module contains an electrolyte of 25% (by weight) potassium hydroxide.

In an 8-hour period the Altus 20 produces 9,600 standard liters, enough to refuel all of the vehicles. Daily deliveries of hydrogen could be possible, if necessary. In the future, SunLine probably will elect to obtain a hythane or hydrogen bus, which will be refueled with the balance of the hydrogen produced.

3.2.4 Hydrogen Gas Chiller

A chiller will be used to condense water out of the hydrogen gas stream. The chiller will cool the gas to ~ 20°C, which will remove the majority of the water from the gas stream. This will reduce the frequency of cycling the gas dryer beds. The gas will be cooled in a tube-in-tube heat exchanger. Hydrogen will flow through the inner tube of the exchanger, while a centrifugal pump will circulate the coolant water in the outer tube. The water extracted from the hydrogen gas stream will drain back into the electrolyte reservoir. The chiller will run whenever the electrolyzer is on and generating hydrogen gas.

3.2.5 Hydrogen Gas Dryer

The hydrogen gas dryer is specifically designed to operate with the Altus 20 electrolyzer and is designed to reduce the moisture content of the gas stream to 1 ppm via a desiccant bed. There are two desiccant beds in the dryer, and when one of them becomes saturated, the second unit is switched in while the first is regenerated. The regeneration process consumes hydrogen gas at a rate of 2 slm for a period of 6 hours. The chiller, which acts as a pre-drying unit, reduces the frequency of dryer recycling and therefore conserves hydrogen. Each bed will be used for 60 hours of before being regenerated.

3.2.6 Hydrogen Compressor

A single continuous length of seamless stainless steel tubing enclosed in conduit that is buried below grade will connect the generation building and the storage area. This line will operate at a pressure of 100 psig and will connect to a ballast tank which precedes the compressor.

A Pressure Dynamic Consultants PDC-4 diaphragm compressor will be used to boost the pressure to 4,000 psig. Diaphragm compressors are designed to pump gases that must remain uncontaminated. Gas purity is ensured by separation of the hydraulic oil and hydrogen by three metallic diaphragms that are sealed by o-rings on each side. In addition, diaphragm compressors have essentially no blow-by. Engineering staff at Teledyne Brown recommended PDC Machines. PDC worked with us to make sure that the unit meets Class 1, Division 2, Group B requirements and can operate under the high-temperature conditions that exist in Palm Desert.

We chose the compressor based on our requirements for inlet and outlet pressure (less than or equal to 1000 psig inlet and 4000 psig outlet), flow rate (greater than or equal to 20 slm), gas purity (greater than 99.99%), and low blow-by (less than 0.1%), as well as on the recommendation of the electrolyzer manufacturer. Once these requirements were met, the least-cost option was chosen.

This compressor is equipped with three pressure switches and an internal pressure relief at the intermediate pressure stage (750 psig). The compressor will run whenever the electrolyzer is on, the storage pressure is below 4,000 psig, and the ballast pressure is above 60 psig. The compressor suction pressure will be controlled to a maximum of 40 psig with a forward pressure regulator (provided by the manufacturer). This pressure was chosen in order to limit the compressor flow capacity to a value that matches the Altus 20 hydrogen generator output of 20 slm. A pressure transducer will be installed just upstream of the pressure regulator to monitor the compressor regulator inlet pressure.

The compressor is also equipped with two leak detection systems (one for each stage) and a compressor cooling system. The leak detection systems will shut the compressor down on a fault if a hydrogen gas leak is detected. The cooling system is provided by PDC to produce chilled water for the compressor interstage cooler and process after cooler.

3.2.7 Hydrogen Storage

Choices for hydrogen storage include compressed gas (bulk and cascade), metal hydrides, and liquid hydrogen. Because of their high cost and complexity, we ruled out metal hydrides and liquid hydrogen. We decided on a bulk storage system because it is less complex, which makes it less costly, easier to use, and more robust. The system requires fewer parts and programming and training of attendants will be easier. The initial cost of materials is lower, and the lifetime is longer, for bulk rather than for cascade storage.

Total hydrogen storage in this area may ultimately amount to approximately 12,000 scf. Initially, about 1,100 scf at 4000 psig will be stored in four high pressure cylinders which are rated to 6000 psig, for transportation to the dispensing station. The remaining 10,900 scf (309 Nm^3) of hydrogen gas will be stored in a single high pressure cylinder mounted horizontally and will be used to refuel hydrogen/natural gas blend buses or other hydrogen powered vehicles belonging to SunLine Transit.

3.2.8 Hydrogen Cylinder Transportation Rig

The hydrogen storage system is designed to allow cylinders to be transported between the hydrogen generation facility at SunLine Transit and the hydrogen dispensing station near City Hall.

A storage rig consisting of four interconnected horizontally mounted cylinders supported by a steel cart will be used (Figure 10.3). Two rigs will be built: one will be charged at the generation facility while the other services the dispensing station. The use of individual cylinders would have required manually disconnecting and connecting each cylinder for each delivery. This process would have required significantly more time for delivery and would have increased the chances of a hydrogen leak.

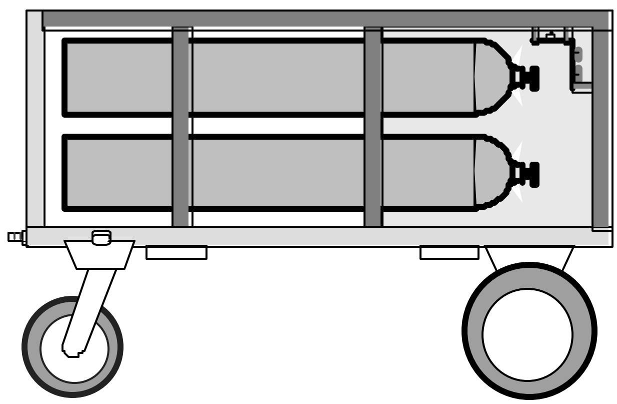

Figure 10.3: Hydrogen Cylinder Transportation Rig

SunLine owns a tilt trailer that they will retrofit with a winch and tie-down connections for transporting the storage rig. This rig consists of 4 cylinders and associated hardware mounted on a manufactured platform truck with four locking pneumatic wheels, two swivel type and two fixed straight type. A pad eye and tie down connections will be added to allow winching and securing the rig onto the transportation trailer. The tie down connections will also be used at the hydrogen generation facility and the dispensing station. Safety chains will secure the rig to the containment wall at each site. If an earthquake occurs, the chains and the locking wheels will constrain the movement of the rig so that the long flexible hoses, which connect the storage rig to the hydrogen system, will not be damaged. The rig will also include forklift sleeves so that it can be moved by a forklift, if desired.

The cylinders are rated to 6,000 psig, have a water volume of 1.32 standard cubic feet each, and are fitted with cylinder valves and pressure relief devices. The cylinder valves have CGA 703 fittings (for high pressure hydrogen).

The four cylinders will be connected through a manifold that includes a pressure relief valve, a pressure gauge, a manual valve, a vent valve, and two quick connect couplings. A dual hose (a high pressure gas hose and a vent hose) will connect to the quick connects. One quick connect allows the storage rig to be connected to the storage area plumbing for charging or to the plumbing at the dispenser storage area panel for dispensing. The other quick connect will provide a means to vent the charging or dispensing hose prior to disconnecting the quick connects.

4. INTEGRATION OF COMPONENTS

4.1 Power Interconnection

We considered three interconnection strategies for the electrolyzer and the PV array: a DC system (where the PVs are directly connected to the electrolyzer); a DC system with maximum power point tracking and a DC-DC converter; and an AC (grid-connected) system, where the PVs feed their power to the grid and the electrolyzer draws its power from the grid.

We chose a grid-connected system to reduce both cost and complexity. With the first two options, there would have been a large number of relays, thicker wires, and other requirements, such as digital control and electrolyzer modification. Maximum power point tracking would have required the purchase of an expensive, made-to-order DC-DC converter. Much of the equipment for a DC system would have been harder to find or more expensive than the equipment for an AC system.

With our grid-connected system, the electrolyzer will be used the way the manufacturer intended for it to be used. Although the unit runs on DC power, it comes with a power supply to rectify the power from the grid. Cost and complexity are reduced, and modifications to the electrolyzer are unnecessary. In addition, the grid will serve as a storage medium for renewably generated electricity. Finally, we will have the option to run the electrolyzer for twenty-four hours a day using green power (which can be purchased in California's deregulated utility environment) to make full use of the hydrogen production capability of the unit.

While designing this system we consulted with Southern California Edison with regard to an appropriate choice of inverters. They recommended that we use either Omnion or Trace inverters as both had been thoroughly tested by the utility for use with their system. A selection of certain models from either of these manufacturers would guarantee rapid approval for connection to the utility grid without the lengthy testing procedure that would be required with other manufacturers. A single Omnion inverter could have handled the power generated by the system, but its cost was substantially greater than three equivalent Trace inverters.

4.2 PV Array Sizing

The photovoltaic system for the Palm Desert Solar-Hydrogen Generation Facility will provide the electrical power to produce hydrogen by electrolysis. The fundamental design criterion for the PV system is that the system's cumulative annual output equals or exceeds the energy the Altus 20 electrolyzer requires to produce the hydrogen sufficient to refuel the vehicles. This quantity of hydrogen was estimated assuming that the three PUVs and one NEV would be refueled five times a week.

The calculation of hydrogen required is as follows. A single refueling for a PUV requires 1380 standard liters (sl); the NEV requires 5200 sl. At five refuelings each week, this amounts to 46,700 sl/week or 2,430,000 sl/year. The Altus 20 electrolyzer produces 20 slm or 1200 sl per hour, so production of the yearly amount of required hydrogen will require 2,020 hours of full power electrolyzer operation during the year. At full output the Altus 20 requires a constant 8.2 kW of AC power to be provided to its AC-DC converter. Thus, to meet the total annual hydrogen requirement, the Altus 20 will consume 16,600 kWh of electrical energy per year. This, then, was the production goal we were seeking in sizing the PV array.

The array was sized by performing simulations using the Transient System Simulation Program (TRNSYS), developed and updated by The Solar Energy Laboratory at the University of Wisconsin, Madison. TRNSYS is a modular program which allows the use of user developed subroutines which can be custom designed to simulate the operation of specific equipment.

SERC personnel have previously developed an extensive array of modeling software that they used to simulate the operation of the Schatz Solar Hydrogen Project in Trinidad, California. This software was designed to be easily configurable to account for broad system variations and as a result, it was very easy to incorporate into TRNSYS.

The solar input data were obtained from the extensive data available from the Department of Energy's Solar and Meteorological Surface Observation Network, Volume III. Although direct data for Palm Desert were not available, extensive data were available for Daggett, a community located approximately 100 miles NNW of Palm Desert and which experiences similar weather. The Daggett data were used and are probably slightly conservative as its location in the "high" desert is somewhat less sunny than Palm Desert located in the "low" desert. This is compensated for, to some extent, by the higher ambient temperatures in Palm Desert.

The Trace inverters have a built in peak-power tracking module with a fairly narrow window of input voltages to accomplish this. As the ASE module's voltage characteristics fall near the lower end of this range under normal operating conditions, we were concerned the array operating voltage would become too low (for the inverter) due to the high ambient air temperatures in Palm Desert. Consequently, the PV sub-routine was designed to monitor the frequency and duration of such occurrences and their effect upon system performance. As it turned out, such circumstances occurred rarely with little effect on performance.

Based on the selected components, the target energy production goal, the solar resource, and various other related parameters, a TRNSYS input file was generated and a series of simulations was performed. The results for an array consisting of 39 ASE-300 DG/50 modules tilted at 30° and facing south are shown graphically in Figure 10.4. As can be seen in the figure, this array was found to generate annual electrical energy of 17,600 kWh, approximately 6% above the production goal. This small excess was judged to be reasonable assurance against less sunny than average years and the possibility that the modules would produce less than their rated power.

4.3 Control System

The purpose of the control system is to monitor and control gas generation and storage, ensure safe system operation, and collect and store operational data. The control system will consist of a Windows-based system control computer (SCC), associated data acquisition and control hardware, and an emergency shutdown circuit. The computer will be located in the control room in the gas generation building. The associated data acquisition and control hardware and the emergency shutdown circuit will be placed in an electrical enclosure that will be mounted on the interior wall of the control room. The control room will be continuously air conditioned to maintain acceptable temperatures for the computer control system. The control computer will communicate with signal and control points that will be located primarily in the gas generation room and the gas storage area.

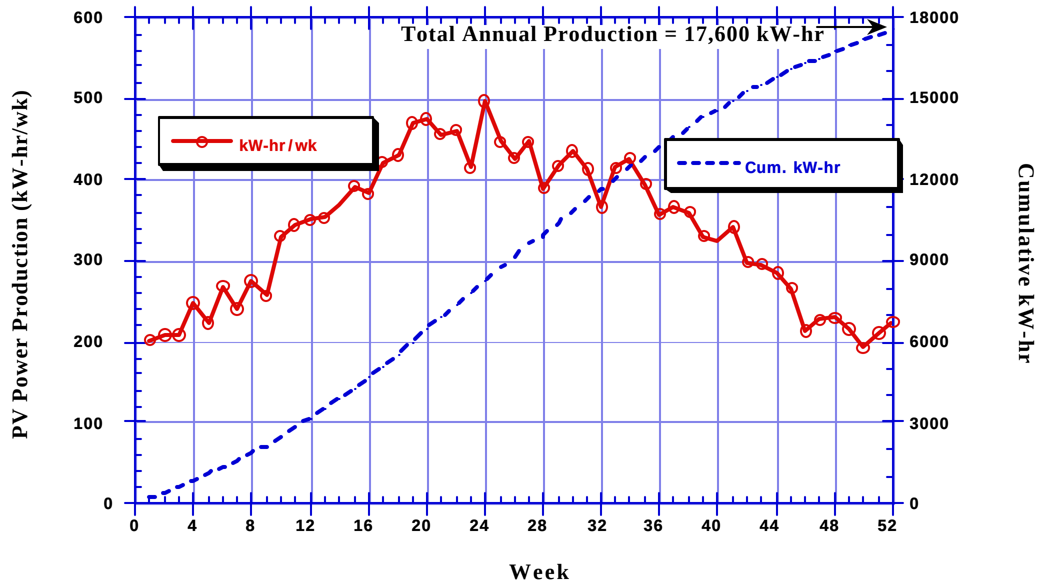

Figure 10.4: TRNSYS Output, Weekly and Cumulative PV Energy Production for 39 Modules

In addition, major components in the hydrogen gas system (electrolyzer, gas dryer, and compressor) will have their own internal control systems that control their operation. These internal control systems allow these devices to operate independently. The system control computer (SCC) will allow these units to operate under their own control mechanisms; however, it will monitor the operational status of these units and will be capable of turning the units on (compressor and dryer) and off (electrolyzer, compressor and dryer). No modifications will be made to the internal control mechanisms of the electrolyzer, gas dryer or compressor.

Generation and storage of hydrogen gas at the hydrogen generation facility will be monitored and controlled by the SCC. To accomplish this, the SCC control system logic will be integrated with the internal control system logic of the electrolyzer, gas dryer and compressor. The SCC will also collect and store operational data for the hydrogen generation and storage system. The SCC will not be relied upon for critical system shutdowns as a hardware-based emergency shutdown circuit will initiate critical shutdowns.

4.4 Emergency Shutdown System

The emergency shutdown system provides a level of safety that is independent of the SCC. If a critical fault condition occurs, the emergency shutdown system will automatically shut down the entire gas generation system.

This circuit is composed of a variety of solid state components and requires a constant voltage input from all of the system critical components. In the event that any of these components enters into an out-of-range or failure situation, the voltage signal is terminated, thus shutting down the entire system. This ensures that a loss of power to any of the safety critical input channels will cause a shutdown. For example, if a wire were to become disconnected from the hydrogen detector, a manual system override button, or any other input channel on the emergency shutdown circuit, a fault would occur and the gas generation system would be shut down.

The components that we have chosen to monitor are discussed in the following subsections.

4.4.1 Watchdog Timer Activated

The watchdog timer is a solid-state relay whose function is to monitor the status of the control computer and to shut down the gas generation system if the control computer hardware or software malfunctions. The control computer software will be required to send a signal to the watchdog timer every 1.6 seconds. If the watchdog timer does not receive a signal within this interval, its normally open contact closure will break power to the emergency shutdown circuit, thereby shutting down the system.

4.4.2 Electrolyzer Differential Pressure Switch Activated

The Altus 20 is designed to maintain a 10 psi differential pressure between the hydrogen and oxygen sides of the gas generation system. Should the pressures approach each other within 3 psi the electrolyzer shuts itself down. By monitoring the output from this switch, the rest of the system will also be shut down if such an event occurs.

4.4.3 Manual System Override (MSO) Button Pressed

There will be four MSO buttons located throughout the site in strategic locations: the control room, the gas generation room, and in two places in the gas storage area. Each of these buttons will be well marked with a sign noting that they are Manual Stop buttons. They will be normally closed push buttons that break the circuit when pressed. This will break power to the emergency shutdown circuit and will activate a system shutdown.

4.4.4 Fire Alarm Activated

The fire alarm can be activated by any of the three smoke detectors installed in the building. One smoke detector will be installed in the gas generation room, one in the control room, and one in the bathroom. This alarm will also be activated if any of the fire alarm pull boxes installed on the site are pulled. One pull box will be centrally located on the front wall of the building near the main door and one will be located at the northern access gate to the site

If the fire alarm is activated, a normally open contact closure will break power to the emergency shutdown circuit, thereby shutting down the gas generation system. In addition to shutting down the gas system via the emergency shutdown system, any event that activates the fire alarm will also sound an audible alarm on site, activate a red flashing light on site, and notify the SunLine Transit Agency’s 24-hour dispatcher of the emergency.

4.4.5 Burglar Alarm Activated

The burglar alarm can be activated by either occupancy sensors or sensors on the windows and doors. This silent alarm system will automatically notify SunLine Transit Agency's 24-hour dispatcher if an alarm is activated. In addition, a normally open contact closure will break power to the emergency shutdown circuit, thereby shutting down the gas generation system.

4.4.6 Hydrogen Detector Activated

The hydrogen detector (C3-HD-1) will be mounted at the highest point in the gas generation room where hydrogen gas is most likely to accumulate if there is a leak. If the detector senses a hydrogen concentration in excess of 1% (25% of the lower combustible limit of hydrogen gas in air), its normally open contact closure will break power to the emergency shutdown circuit, and shut down the system.

4.4.7 Exhaust Vent Position Switch Activated

To ensure that there is always adequate ventilation in the gas generation room when hydrogen gas is being generated, two safety switches have been incorporated into the system. One is a vent position switch. This switch will monitor the position of the operable exhaust ventilation louvers that are going to be installed in the wall of the gas generation room. If the louvers are shut the switch will open, sending a fault signal to the emergency shutdown circuit, causing a system shutdown.

4.4.8 Ventilation Flow Switch Activated

A ventilation flow switch will also be used to ensure that there is adequate ventilation in the gas generation room when hydrogen gas is being generated. This switch will be mounted in the intake ventilation fan housing and will open if the air flow into the gas generation room drops below approximately 500 cf/min (14 m^3/min). This will send a fault signal to the emergency shutdown circuit and will cause a system shutdown.

4.4.9 Power Failure Detected

An Uninterruptible Power System (UPS) will provide conditioned power to the SCC and associated control hardware. This will allow the control system to ride through momentary voltage sags on the power grid without shutting down the system. If the power from the grid is lost, the UPS will detect the power failure. A relay contact on the UPS system will open when grid power is lost. This relay will be used to send a signal to the emergency shutdown circuit that will cause a system shutdown.

4.4.10 Status Beacon

In addition to shutting down critical loads, the emergency shutdown circuit will operate a status beacon that indicates the status of the gas generation system. Three status lights will be mounted in a stacked fixture on the front wall of the building near the main door. The lights will be turned on and off using electromechanical relays. During normal operation the green status light will be lit. When the system is shut down by the fire alarm system (activated by a smoke alarm or fire alarm pull box) the red light will be lit. If the system is shut down due to other less serious alarms (i.e. manual stop button pressed, burglar alarm activated, hydrogen detector activated, watchdog timer activated) the yellow light will be lit.

4.4.11 Electrolyzer External Alarm

In the event of a system fault, the emergency shutdown circuit will shut down the electrolyzer via an external alarm input on the electrolyzer. An electromechanical relay will be used to control this alarm. When a shutdown is activated the relay will open and the electrolyzer will be shut down on an external alarm fault.

5. PUBLIC ACCEPTANCE AND SAFETY ISSUES

The initial impetus for this project came from members of the Palm Desert City Council who approached SERC. At that time, there was a great deal of enthusiasm expressed by the City Council in general, with no apparent impediments. However, over time the membership of the council changed somewhat while the financial state of the city deteriorated. As a result, resistance to the project began to grow. The proposed site for the hydrogen generation facility was challenged by a citizens group seeking the construction of a skateboard park. Faced with this public pressure, and after two years of negotiating with us, the council decided that they would rather have a skateboard park than the solar hydrogen generation station.

The site was then shifted to the campus of The College of the Desert (COD). Again, there was initial enthusiasm and acceptance of the project, but a small vocal minority in the administrative branch of the college was opposed to the project from the start.

During this time SERC took a proactive approach to the safety issue and held a public meeting at which all of the various concerns could be addressed. The meeting was quite successful with the public, the local fire marshal, and many members of COD administration. Unfortunately, the dissenting minority from COD was unswayed and preferred to ask alarmist questions such as the classic “What about the Hindenburg explosion?“ COD had also raised the issue of liability insurance, but COD’s insurance representative, who was invited, failed to attend.

Eventually, COD administrators, acquiescing to the demands of the anti-hydrogen contingent, demanded massive indemnification for the coverage of such environmental disasters as “hydrogen spills“ and the contamination of groundwater and wildlife. When it became clear that the COD administrators would not outright deny permission for the project to proceed, but intended to use extended delaying tactics to achieve their goal, arrangements were made to install the facility at the SunLine Transit Agency. Unfortunately, a great deal of time and effort had already been expended on the design for the COD site.

The SunLine Transit site is already being used as a refueling station for buses that operate on compressed natural gas, so the production and storage of hydrogen was welcomed by Sunline officials. Indeed, Sunline sees our hydrogen station as a natural evolution to a cleaner fuel. As this site is privately owned and quite sizable, no further opposition to this project has been heard. We are now awaiting word from DOE on further funding to complete the station.

Since the inception of this project we have been very concerned with safety. Beginning with the design and construction of the first PUV we have enlisted Hoes Engineering, Inc. of Davis, California to provide us with a detailed safety analysis of all aspects of this project.

Hoes Engineering specializes in the field of safety engineering and has done extensive work for NASA. They have developed an interactive computer program called HAZTRAC that they have designed to help identify and address possibly hazardous elements in any design. The program is used in an iterative fashion with a substantial amount of back and forth between the client (SERC in this case) and Hoes Engineering. They have reviewed almost all phases of our design work including architectural plans, gas handling and storage systems, electrical systems, and refueling systems. All conceivable hazards were identified and addressed in terms of:

- Hazard scenario
- Effect
- Risk assessment
  - catastrophic
  - critical
  - marginal
  - negligible
- Remarks
- Recommendations to minimize risk

We have also consulted them extensively for guidance through the labyrinth of building codes and their application to our project. When construction is complete, they will inspect the installation and review the refueling station software.

6. CONCLUSIONS

Upon its completion, the Palm Desert Renewable Hydrogen Transportation Project will be a unique demonstration of state-of-the-art technology encompassing the hydrogen fuel cycle from production to final use. As the project currently stands, it is already unprecedented in that a small fleet of fuel cell powered vehicles is in daily use by ordinary citizens. The potential for providing Zero Pollution Vehicles to the general public with the attendant environmental benefits can be clearly seen in Palm Desert at this moment.